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Search for spatial anisotropy in β-decays

Eugeniy Novikov and Pavel Pakhlov

Institute of Theoretical and Experimental Physics
B.Cheremushkinskaya, 25, 117259, Moscow, Russia

Abstract. Theoretically a possibility of covariance violation in weak decays is not ruled out from the first principles, while there are some models predicting non-covariance revealed in weak interactions. The experimental evidence for isotropy violation in β-decays was recently reported. We present a study of the dependence of electron flow rate and β-electron energy in the decay of Sr^{90} with respect to the direction of electron emission. An upper limit of $1.4 \cdot 10^{-5}$ on directional dependence of β-electron energy was obtained.

1 Introduction

Possible non-covariance of laws of nature was searched intensively during this century. Experimentally no evidence of covariance breaking in general relativity and electrodynamics was observed in the famous Eötvös and Hughes-Drever experiments [1, 2]. These precise experiments narrowed the field of possible non-covariant models, but still left a room for them.

Non-covariance, in particular Lorentz non-invariance, was proposed to be searched in weak decays by Rédei in 1966 [3]. He extrapolated to weak decays the argument of Blokhintsev [4], who pointed out that possible existence of the universal length parameter violates the Lorentz invariance by introducing a preferred Lorentz frame, where this parameter is measured. In Rédei's approach the lifetime of weakly decaying particles turns out to be anomalously dependent on their boost:

$$\tau(v) = \gamma\tau_0(1 + \gamma^2 a_0^2), \tag{1}$$

where τ_0 is the lifetime in the preferred frame and a_0 is the universal length parameter. Experimentally an indication of the anomalous dependence of the lifetime of charged pions and kaons on their boost was observed, while a strict limit for such a dependence was obtained for muon decays [5]. Since the covariance violation mechanism was supposed to be the same for muons and hadrons the latter measurements were considered to rule out Rédei's hypothesis at a high accuracy level.

In the end of 70-th the question of non-covariance in weak decays was renewed by Nielsen and Picek [6]. They proposed not a vector but a tensor covariance breaking mechanism by introducing a non-covariant metric into the Higgs kinematic term $h^{\mu\nu}D_\mu\phi(D_\nu\phi)^*$, where $h^{\mu\nu}$ is different from the metric tensor $g^{\mu\nu}$. Such a term results in non-covariant observables in weak decays, while electrodynamics and gravitational sectors remain covariant. Indeed, the new metric is revealed in a gauge boson mass term ($h^{\mu\nu}A_\mu^a A_\nu^a\langle\phi\rangle^2$) and results in a tensor structure of the Fermi constant: $G_F^{\mu\nu} = \frac{\sqrt{2}g_2^2}{8h^{\mu\nu}\langle\phi\rangle^2} \simeq \frac{\sqrt{2}g_2^2}{8m_W^2}(g^{\mu\nu} + \xi^{\mu\nu})$. In [6] the metric $\xi^{\mu\nu}$ is assumed to be isotropic but not Lorentz invariant. In the simplest form it is parametrized by a single parameter α ($\xi^{\mu\nu} = \alpha\ \mathrm{diag}(1, 1/3, 1/3, 1/3)$). Under these assumptions the dependence of the lifetime of weakly decaying particles on their boost is derived. It turns out that the lifetime of charged pions and kaons is affected by the additional boost term in a way similar to the Rédei approach, while for muons the effect cancels out.

In the last decade the arguments in favor of Lorentz invariance violation came from the string theory, where non-local objects – strings can lead to the spontaneous breaking of the covariance [7]. The covariance-violating term is generated when tensor rather than scalar

fields gain the vacuum expectation values. If this tensor field couples to the weak gauge bosons we come to the approach of Nielsen and Picek.

The metric $\xi^{\mu\nu}$ being anisotropic leads to visible anisotropy in weak decays, which can be searched for experimentally. Assuming the simplest one-parameter case ($\chi_{\mu\nu} = \alpha\ \mathrm{diag}(1,0,0,1)$) the flow rate of daughter particles in weak decays is calculated to be direction dependent. Consider for example muon decay at rest.

$$\mu^+(p) \rightarrow e^+(k) + \nu_e(q_1) + \bar{\nu}_\mu(q_2). \tag{2}$$

Following calculations from [6] non-covariant term in muon differential width is equal to:

$$\begin{aligned} \frac{d\Gamma}{dk\,d\cos\theta\,d\phi} &= \frac{G_F^2 k \chi_{\mu\nu}}{24\pi^4 m}(2q^2 p^\mu k^\nu + (p\cdot k)q^\mu q^\nu - (k\cdot q)p^\mu q^\nu - \\ &-(p\cdot q)k^\mu q^\nu) = \frac{G_F^2 k\alpha}{24\pi^4 m}(m^3(m-3k) - k^2 m^2 \cos(2\theta)), \end{aligned} \tag{3}$$

where q is the sum of the two neutrino momenta $q = q_1 + q_2 = p - k$ and θ is the angle of the electron momentum with respect to z-axis (further referred as “preferred axis”). The integration over electron momentum and polar angle ϕ gives:

$$\frac{d\Gamma}{d\cos\theta} = (1 + 2\alpha\cos(2\theta))\frac{d\Gamma_{SM}}{d\cos\theta}. \tag{4}$$

The β-decays of neutron and nuclei are calculated in a similar way. The β-electron rate exhibits a similar directional dependence:

$$\frac{d\Gamma}{d\cos\theta} = (1 + A\alpha\cos(2\theta))\frac{d\Gamma_{SM}}{d\cos\theta}, \tag{5}$$

where A is $\mathcal{O}(1)$ and depends on nuclear form-factors.

An indication of the anisotropy of the light propagation through the Universe published in [8] gives another argument in favor of isotropy violation, though on macro scales. In particle physics an evidence of the directional dependence of the β-decay rate was reported recently [9]. In this paper we present our study of such a dependence. The upper limit for the spatial anisotropy obtained here is much stricter than the effect reported in [9].

2 Experimental Setup

The dependence of β-decay of Sr^{90} on the direction of the electron emission was studied. To detect β-electrons two different options were used: scintillators viewed by photomultipliers and pad silicon detectors. The detectors were placed in front of a radioactive source of an intensity of 15 mCi corresponding to 10^8 decays per second at a distance of 4 cm (figure 1).

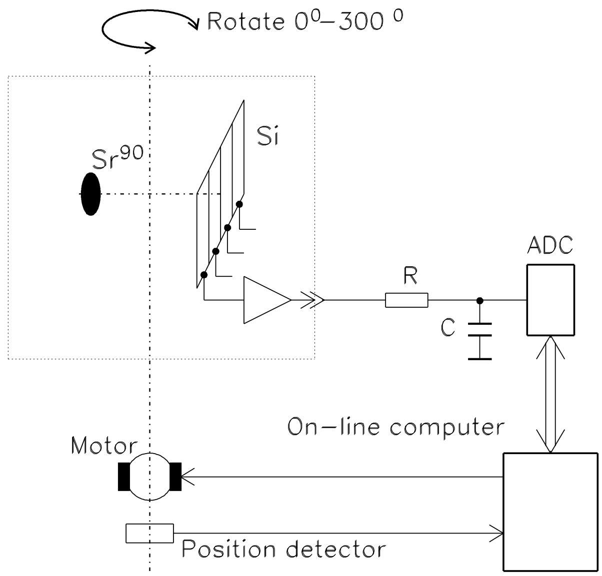

Figure 1: The sketch of the experimental setup.

The plastic scintillator had an area of 12×20 mm^2 and a thickness of 10 mm. The *Hamamtsu-5600U* photomultiplier was attached to a side of the scintillator. Signal from the photomultiplier exceeded the discriminator threshold of 30 mV (corresponding to electron energy $\sim$ 200 keV) was counted by commercial CAMAC scaler during some exposure time. The timing was provided by a quartz timing unit with a time stability of better than 10^{-5}.

The silicon detector consisted of 4 rectangular pads with an area size of 15×20 mm^2 and a thickness of 300 μ. Signals from the silicon pads were amplified by operational amplifiers. Under high electron rates with moderate time characteristics of the amplifier, we had to integrate the signals, rather than count them. Thus the β-electrons energy deposition was measured with silicon detector. Signals were integrated by RC-circuit with integration time of 250 μsec and read out with a frequency of 5 kHz by commercial ADC. The successive readings thus were not totally independent, their correlations were taking into account while the data was analyzed.

In order to measure the decay rate in different directions, it was possible to use the daily rotation of the Earth, keeping the measuring device at a fixed position (as in [9]). However, in this case a very high stability of the measurement conditions should be provided during days. High voltage and threshold potentials could change because of daily temperature and humidity variations resulting in a variation of the decay rate count with time which is a source of irreducible systematic error. The required stability seems unrealistic for the measurements with the accuracy of the order of 10^{-5}. Therefore the decision was to rotate the experimental setup artificially with minimal period such that the environment parameters could not change significantly. The Monte Carlo simulation with the actual characteristics of

our device shows that the rotation with a period of a few minutes guaranteed the systematic changes of the count rate to be much smaller than the statistical error of its measurement.

The shielded source, detector, preamplifiers and power supply units were installed on the platform, rotated by an electric motor in the horizontal plane. The number of counts from the PM or the integrated charge from the silicon detector were measured during exposure time of ~ 4 sec, then the platform was rotated by 30^0 and the measurement was repeated. The number of steps of single 30^0 rotations in one direction was equal to 10 scanning the angle of 300^0, then the measurements were repeated rotating in the opposite direction. The measurements were carried on continuously during 9 days.

3 Data analysis and results

With the first option of the electron detector (photomultiplier) we faced the irreducible source of systematic error. Since the amplification of the PM is influenced by the external magnetic field and the vector of the Earth magnetic field changed relative to the PM while rotated, we observed a non-uniform behavior of the count rate at different directions. To reduce this effect we used active compensation of the Earth magnetic field which allowed to suppress it by a factor of 100. The measurements showed that even with these special efforts, the observed nonuniformity of the PM counts was of the order of 10^{-4}. The count rate dependence on the position of the rotating platform is shown in figure 2 for two hours of data taking. The well seen sinusoidal behavior is explained by the dependence of PM

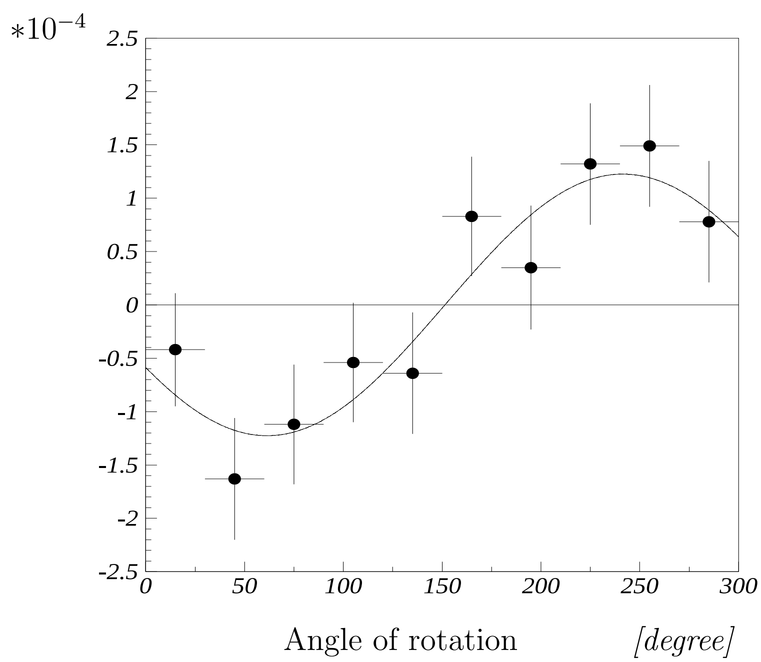

Figure 2: The relative difference of PM counting rate versus angle of rotation.

amplification on magnetic field projection. This was proved by changing the vector of the external magnetic field using the active magnetic compensation. Thus this option was used only for checking of our sensitivity to the non-uniform effects.

The silicon detectors are not affected by the magnetic field at the required level of accuracy. From the other hand the silicon detector and preamplifiers are much more sensitive to the temperature variations as demonstrated by figure 3. The integrated charge in the silicon detector depending on time during 9 days of data taking is presented in figure 3. The prominent periodical local maxima and minima are due to day-night temperature variation

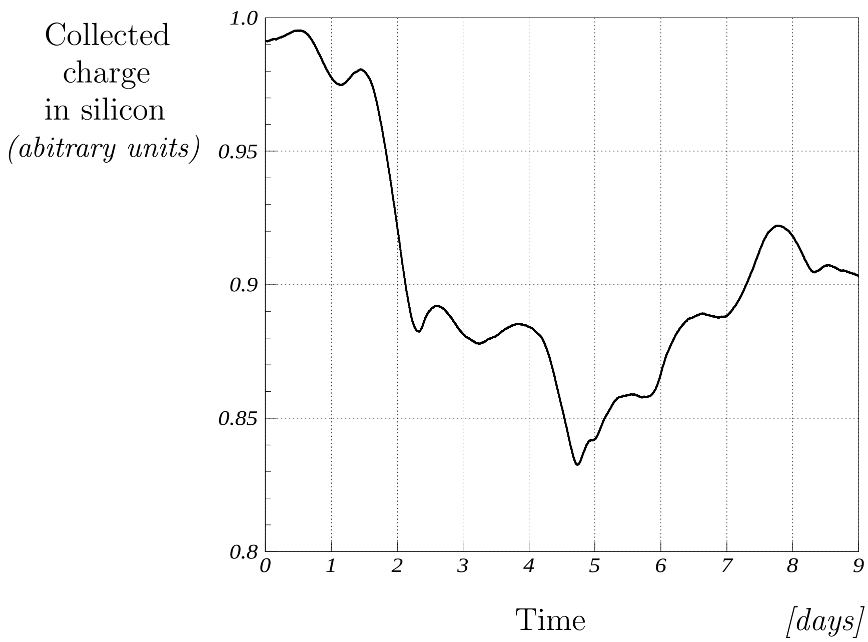

Figure 3: Time dependence of the collected charge in the silicon detector.

of about 3^0 C. This instability resulted in only small error in non-uniformity measurements using the frequent rotations for different direction scanning.

The statistical error of the measurement of the integrated charge during one step of measurement was calculated from the statistical fluctuations of two subsequent steps of measurements. The differences of values obtained in all pairs of successive measurements were plotted and than fitted with Gaussian function. For cross check we also derive the statistical error from the RMS of the ADC readings during one step of measurement, taking into account the correlation between two successive readings of charge from ADC (reading with interval of 200 μsec while the integration time of RC-circuit is 250 μsec). Both ways gave the similar values within 5%. Finally we confirm the extracted from the data values of the statistical errors by numerical calculations.

Each day of data taking was divided into 12 time intervals of $\sim$ 2 hours. During each

interval the Earth orientations was assumed to be the same. For each time interval the charge collected on four silicon pads for each orientation was summed up taking into account consecutive shifts in the position of each pad. Thus, the analyzed data contains information from 10 points of different orientation of the device relative to the Earth and 12 points of different Earth orientations. The data is presented in the form of 12 histograms in figure 4. Each of 12 histogram contains the dependence of the collected charge on the angle of the rotation of the device for some Earth position. All distributions was normalized to unity and unity was then subtracted, thus demonstrating only the net studied effect. Nowhere a signal of non-uniformity is seen.

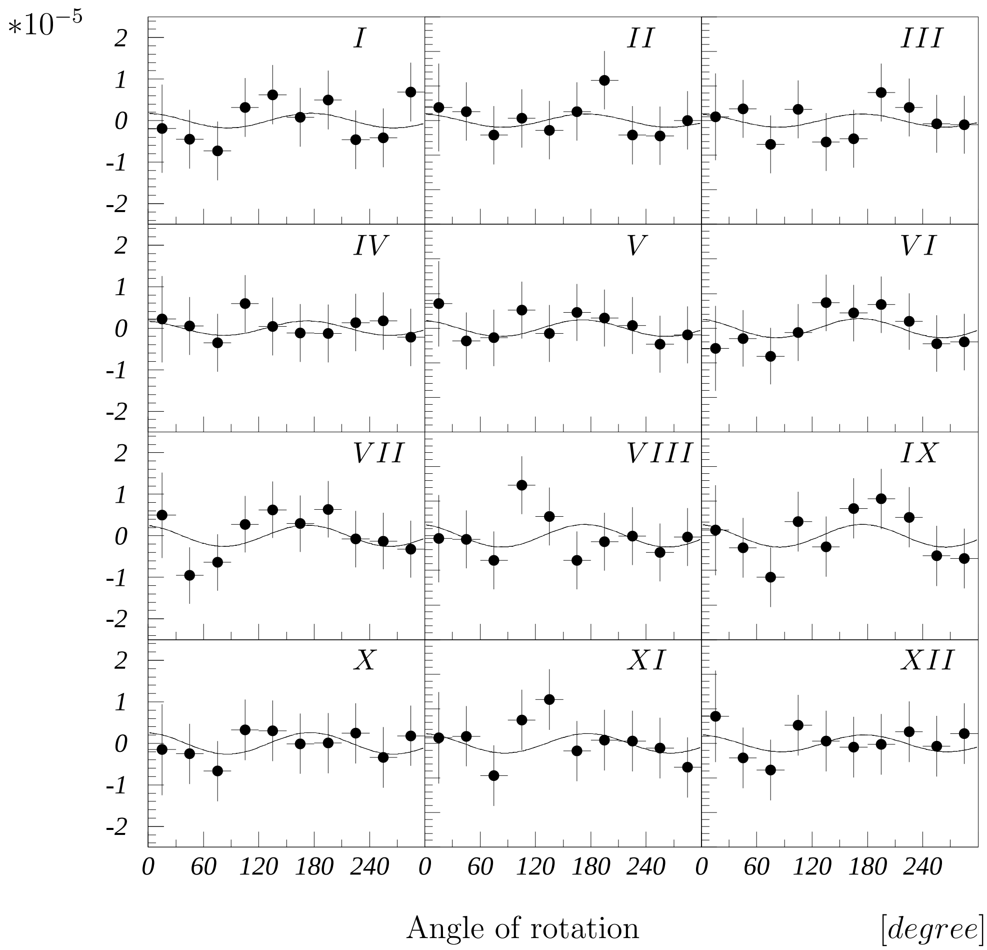

Figure 4: Relative difference in the collected charge in the silicon detector versus the angle of rotation for the 12 (**I-XII**) intervals of time. The solid line represents the best fit curve.

The orientation dependent behavior of the β-electron energy deposition assuming the model discussed in the introduction section is the following:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} \sim 1 + A(t) \cdot \cos\left(2\theta + \phi_0(t)\right), \tag{6}$$

where the angle θ is the angle of the rotation of our device with respect to the axis south-

north. The amplitude $A(t)$ and the phase of the cosine $\phi_0(t)$ change with time because of the Earth rotation as shown in figure 5. Different lines represent $A(t)$ and $\phi_0(t)$ behavior for

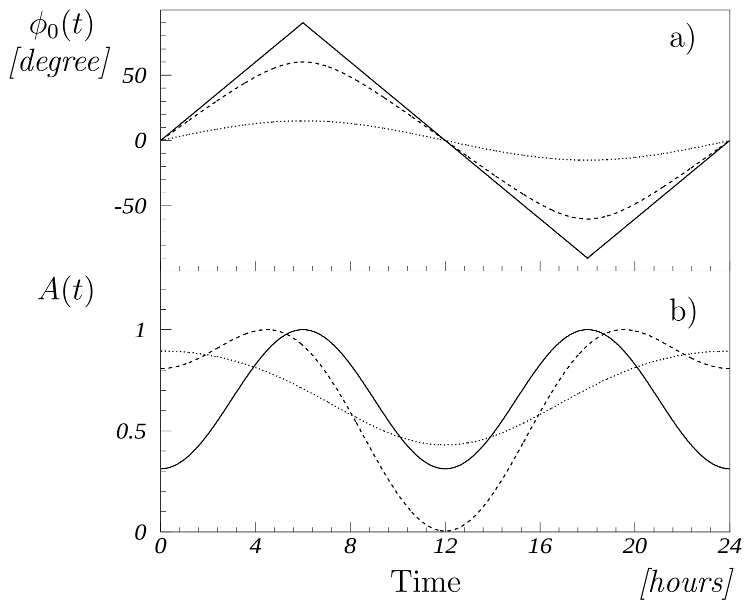

Figure 5: Time dependence of the initial phase $\phi_0(t)$ (a) and the amplitude $A(t)$ (b) from the formula (6) on time for the latitude of Moscow. The solid, dashed and dotted lines are plotted for the angle between z-axis and the axis of the Earth rotation equal to 90^0, 60^0 and 15^0, respectively.

different angles between the axis of the Earth rotation and the preferred axis for the latitude of the place of the experiment. One concludes that whatever the orientation of the preferred axis in the Universe, the non-uniformity of the electron flow is visible at least sometimes during the twenty four hours.

To set an upper limit for the dependence of electron energy on direction, these 12 histograms were fit simultaneously by a function with three free parameters: amplitude of the effect and two variables to describe direction of the preferred vector in the Universe. For each of 12 histograms the fitting function corresponds to the formula (6), while $A(t)$ and $\phi(t)$ are different for different histograms and are functions of three parameters described above.

The fit gives the value $A = (6.7 \pm 3.6) \cdot 10^{-6}$ for the amplitude of the effect. The upper limit, derived from likelihood function, is calculated to be $1.4 \cdot 10^{-5}$ at the 90% confidence level.

4 Summary

Dependence of the rate and energy deposition of β-electrons from Sr^{90} decays on the direction of emission was investigated. Unlike the previously stated evidence for such a dependence

in [9], no signal of the non-uniformity in β-electron flow was observed. The upper limit on the amplitude of non-uniform behavior of $1.4 \cdot 10^{-5}$ was obtained.

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